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EVALUATING EFFECTIVENESS OF A FRIGATE IN AN ANTI-AIR WARFARE (AAW) ENVIRONMENT

by

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June 2016

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13. ABSTRACT (maximum 200 words)

Designing naval ship capabilities for shipbuilding is a challenging process requiring comprehensive technical and tactical studies. Technical studies involve ship design characteristics such as engineering, weapon, and support systems. Tactical studies include the anticipated area of operation, expected threat, the capabilities of the enemy, and potential missions to accomplish. Both studies are used in ship design to determine the ship's required combat capabilities before finalizing the hull design. This research uses the agent-based modeling tool Map Aware Non-Uniform Automata (MANA) to explore the best combat capabilities for a frigate in an anti-air warfare (AAW) environment. Regression and partition trees are used to analyze factors that influence the measures of the friendly frigate's survivability and number of enemy casualties. This study also investigates the use of a prospective ship-based unmanned aerial vehicle (UAV) in AAW operations. We find that the inclusion of Point Defense Missile Systems with long and medium range surface-to-air missiles has the most positive effects on ship survivability. By contrast, we find inclusion of a UAV in this mission has little effect.

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EVALUATING EFFECTIVENESS OF A FRIGATE IN AN ANTI-AIR WARFARE (AAW) ENVIRONMENT

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ABSTRACT

Designing naval ship capabilities for shipbuilding is a challenging process requiring comprehensive technical and tactical studies. Technical studies involve ship design characteristics such as engineering, weapon, and support systems. Tactical studies include the anticipated area of operation, expected threat, the capabilities of the enemy, and potential missions to accomplish. Both studies are used in ship design to determine the ship's required combat capabilities before finalizing the hull design. This research uses the agent-based modeling tool Map Aware Non-Uniform Automata (MANA) to explore the best combat capabilities for a frigate in an anti-air warfare (AAW) environment. Regression and partition trees are used to analyze factors that influence the measures of the friendly frigate's survivability and number of enemy casualties. This study also investigates the use of a prospective ship-based unmanned aerial vehicle in AAW operations. We find that the inclusion of a Point Defense Missile System with long and medium range surface-to-air missiles has the most positive effects on ship survivability. By contrast, we find the inclusion of a UAV in this mission has little effect.

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LIST OF ACRONYMS AND ABBREVIATIONS

AAW	Anti-Air Warfare
AICc	Corrected Akaike Information Criterion
ASM	Anti-Ship Missile
CIWS	Close-in Weapon System
DOE	Design of Experiment
EINSTein	Enhanced ISAAC Neural Simulator Toolkit, where ISAAC is Irreducible Semi-Autonomous Adaptive Combat.
ISR	Intelligence, Surveillance, and Reconnaissance
LCS	Littoral Combat Ship
MANA	Map-Aware Non-uniform Automata
MASON	Multi-agent Simulator of Neighborhoods / Networks
MOE	Measure of Effectiveness
NATO	North Atlantic Treaty Organization
NOLH	Nearly Orthogonal Latin Hypercube
NPS	Naval Postgraduate School
PDMS	Point Defense Missile System
Repast	Recursive Porous Agent Simulation Toolkit
SAM	Surface-to-Air Missile
TERN	Tactically Exploited Reconnaissance Node
UAV	Unmanned Aerial Vehicle
WISDOM	Warfare Intelligent System for Dynamic Optimization of Missions

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THESIS DISCLAIMER

The reader is cautioned that the computer programs presented in this research may not have been exercised for all cases of interest. While every effort has been made within the time available to ensure that the programs are free of computational and logical errors, they cannot be considered validated. Any application of these programs without additional verification is at the risk of the user.

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EXECUTIVE SUMMARY

The combat capabilities of a future naval ship have to be considered thoroughly in the ship design process. These capabilities should be determined before the ship's hull design is complete to make operational effectiveness independent from physical design considerations. The use of simulation with advanced experimental designs provides useful insights about the required combat systems in expected missions the ship must undertake.

This thesis uses the Map Aware Non-Uniform Automata (MANA) combat modeling tool to identify the best combination of weapons and radar characteristics onboard a frigate in an anti-air warfare (AAW) environment. The effectiveness of a prospective ship-based unmanned aerial vehicle (UAV) in an AAW operation is evaluated, as well. We develop an AAW scenario in MANA to investigate key weapons, sensor, and UAV effectiveness on ship survivability and enemy casualties. The MANA scenario representation appears in the following figure. It shows a lone AAW frigate threatened by missile-carrying aircraft and land launched anti-ship missiles from the shore.

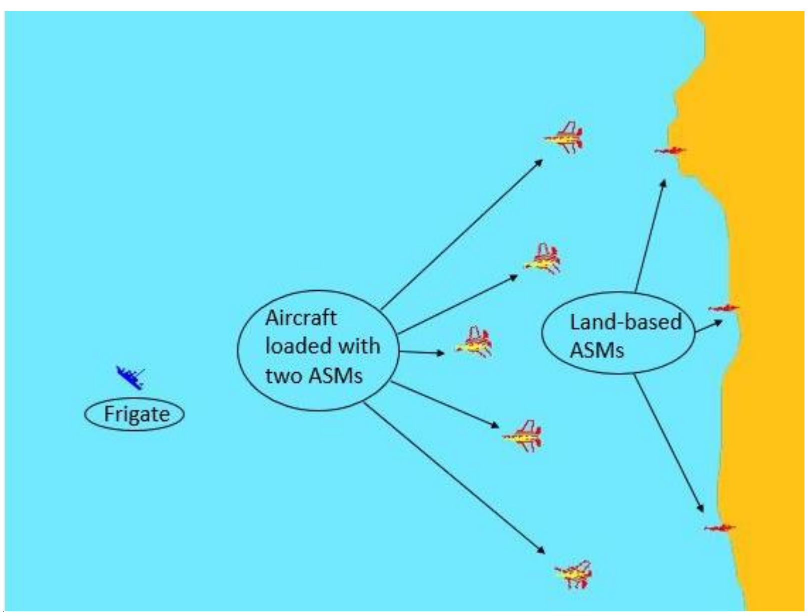

Figure1. Screenshot of the AAW Tactical Scenario Modeled in MANA

The frigate's combat defense system is limited to four weapon systems due to space restrictions. A gun system is always preferred to be onboard due to its versatility in a variety of missions. The other three weapon systems consist of two types of surface-to-air missile systems (SAM) and either a Close-in Weapon System Gatling gun (CIWS) or a Point Defense Missile System (PDMS). These three weapon systems are changed in the experimental design to determine the best mix of weapon types for an AAW frigate in this tactical scenario. For the evaluation of the sensor capabilities we also vary the range of the radar from 40,000 meters to 250,000 meters in the experimental design. The candidate weapons and their specifications are as shown in the following table.

Table 1. Candidate Weapon Types and Specifications

Weapon	**Minimum Range / P (Hit)**	**Maximum Range / P (Hit)**	**Target Type**
CIWS	1,000 m / 0.6	6,000 m / 0.4	Only missiles
PDMS	1,000 m / 0.8	9,000 m / 0.6	Only missiles
Gun	8,000 m / 0.3	14,000 m / 0.2	Both aircraft and missiles
Short Range SAM	5,000 m / 0.8	30,000 m / 0.3	Both aircraft and missiles
Medium Range SAM	10,000 m / 0.8	70,000 m / 0.1	Both aircraft and missiles
Long Range SAM	10,000 m / 0.8	200,000 m / 0.1	Both aircraft and missiles

We use regression analysis and partition trees to analyze the results of 25,700 simulated battles. The analysis shows that the most important design factors for frigate AAW operations is the selection of CIWS or PDMS. Furthermore, it shows that the PDMS is superior to CIWS in enhancing ship survivability and inflicting enemy casualties. This study also demonstrates that longer range SAMs, the combination of the SAMs onboard, and longer radar range have significant impacts on the success of an AAW operation. In addition, this research provides evidence that the use of a medium range UAV in an AAW environment does not substantially contribute to mission success. Longer range UAVs with greater surveillance capabilities may have more effect, but they are not explored in this study.

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I. INTRODUCTION

A. OVERVIEW

Designing naval ship capabilities for shipbuilding is a challenging process requiring comprehensive technical and tactical studies. Technical studies involve ship design characteristics such as engineering, weapon, and support systems. Tactical studies include the anticipated area of operation, expected threat, the capabilities of the enemy, and potential missions to accomplish.

Designing a naval ship is also a complicated process because it requires developing a system of systems (Mizine, Wintersteen, & Wynn, 2012). This article also states that since these systems interact and influence each other the developmental process is even more challenging. If we consider an entire fleet architecture rather than an individual ship design, this challenging work becomes further complicated. Moreover, a variety of expected threats need to be considered during the ship design process as well. For example, in an anti-air warfare (AAW) mission, weapons and radar systems influence each other and interact with the combat software system (Figure 1).

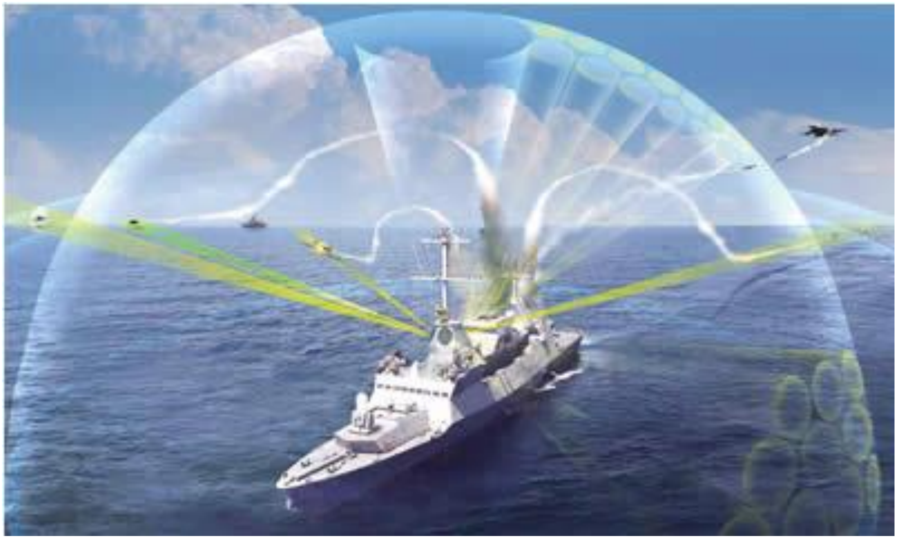


Figure 1. A Naval Ship in an AAW Environment.
Source: Oneindia News (2015).

Successfully defending naval ships from air threats depends mainly on force capabilities and the tactics of each opposing side. Considering the air defense capabilities of our forces against an enemy, an AAW frigate should be able to detect and eliminate enemy aircraft and guided missiles while deterring other threats, such as submarines, small craft, and other surface ships. To achieve this tactical objective, the ship's weapon configuration should be determined as part of new ship construction design.

There is limited space onboard a frigate; therefore, selecting the most effective combination of weapon systems to be included in the ship's design is a matter of great importance.

B. RESEARCH QUESTIONS

This research focuses on the following questions related to the improvement of the ship design process:

- Among a set of air defense weapon systems alternatives, what is the most effective combination for a future AAW frigate design?
- How effective are Point Defense Missile Systems (PDMS) compared to Close-in Weapon Systems (CIWS) with different weapon configurations?
- Does employing an unmanned aerial vehicle (UAV) onboard an AAW frigate have significant advantages in an AAW mission?
- What is the probability of survivability against enemy air assets with different weapon combinations?
- What are the strengths and drawbacks of utilizing Map Aware Non-Uniform Automata (MANA) to construct realistic scenarios for evaluating AAW effectiveness of naval ships?

C. SCOPE OF THE THESIS AND METHODOLOGY

This thesis' main focus is evaluating the effectiveness of different combinations of weapon types and radars onboard a frigate in a realistic AAW environment with the intent to inform Turkish AAW frigate design. This study also explores how a UAV like the MQ-9 (Figure 2) can contribute to mission success by providing early warning to surface ships.

Figure 2. USS Fort Worth (LCS-3) Launches First UAV. Source: America's Navy (2013).

We use an agent-based simulation modeling platform called MANA to model AAW scenarios, allowing us to assess the defensive capabilities of alternative combat system configurations on a future AAW frigate. “Agent-based simulations are models where multiple entities sense and stochastically respond to conditions in their local environments, mimicking complex large-scale system behavior” (Sanchez & Lucas, 2002).

We create a base case tactical situation, threat, and combatant configuration in MANA for comparing alternatives. In the base case, a single AAW frigate is threatened by three enemy land-based anti-ship missiles (ASM) and two enemy aircraft each loaded with two ASMs. The AAW frigate has a medium-range air defense missile system (12 SAMs), short-range air defense missile system (16 SAMs), and CIWS.

In alternative scenarios the number of land-based ASMs and aircraft are varied. The weapon configuration and the radar range of the friendly frigate is also changed for each scenario.

After creating the model in MANA, a Nearly Orthogonal Latin Hypercube (NOLH) design is used to design a set of experiments by varying factors of threat and weapon capabilities. To analyze the output of the experiment, statistical summaries, multiple regression, partition trees, plots, and graphs are used.

D. CHAPTER OUTLINE

Chapter II is the literature review. It summarizes the basic concepts of the AAW mission and layered air defense systems, informs the reader about UAVs that can take off and land on small surface ships such as frigates or littoral combat ships (LCS), and discusses the agent-based simulation and modeling tool MANA.

Chapter III contains the model development and descriptions of scenarios. Agent types with their specifications and the modeling assumptions are explained in this chapter as well.

Chapter IV discusses the exploration of the model. It begins with an overview of the design of experiment used for the simulations; then, it explains controllable and uncontrollable factors. It continues with a detailed analysis of the model output using several data analysis techniques, such as least square regression and partition trees. It closes with a discussion of the significant factors discovered from the analysis.

Chapter V concludes the thesis with a summary of the study, recommendations, and suggestions for further research.

II. LITERATURE REVIEW

The traditional approach in naval warship building is to design combat systems around the hull vessel platform. The platform, however, should be designed around the combat systems to build more effective warships. During the early conceptual design of a combat ship, computer simulation models, and experimental designs provide useful insights about the required weapon systems, radars and other combat systems (MacCalman, Beery, & Paulo, 2016). Therefore, operational effectiveness becomes independent of physical design considerations. In this study, our aim is to evaluate different operational characteristics of a frigate in an AAW environment to decide the best mix of weapons and sensors. In addition, we examine contributions of a prospective UAV in anti-air warfare.

A. ANTI-AIR WARFARE

The North Atlantic Treaty Organization (NATO) describes anti-air warfare as “measures taken to defend a maritime force against attacks by airborne weapons launched from aircraft, ships, submarines and land-based sites” (Anti-air warfare, 2015) (Figure 3).

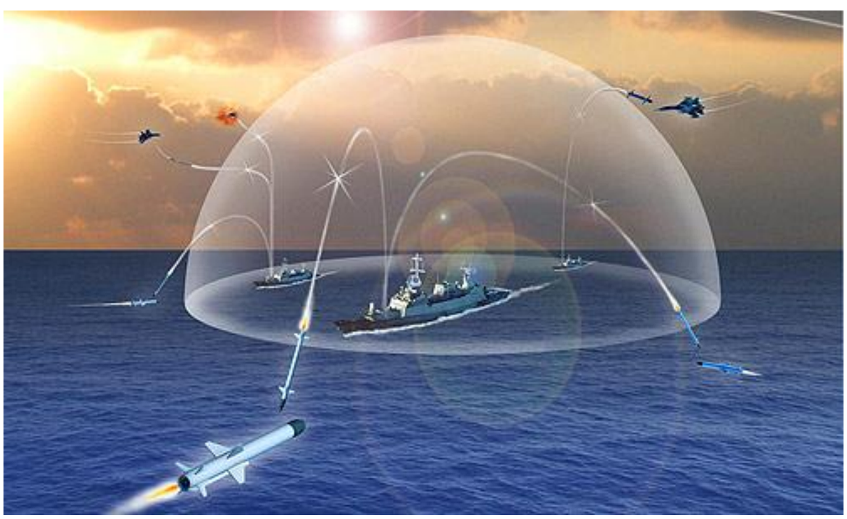


Figure 3. Anti-Air Warfare. Source: Defence News (n.d.).

According to Defencyclopedia, today's missiles are in common use among world navies due to their long ranges and accuracy (Defencyclopedia, 2014). The website further describes that most defense industry companies sell these deadly missiles at affordable prices to allow many countries to easily employ them onboard their warships. Missiles also offer massive destruction compared to large caliber guns (Figure 4).

World navies prefer anti-ship missiles not only for their accuracy and long ranges, but also for their simplified launch procedures and maintenance simplicity. For ships operating near enemy ASM sites, there is a need for a defensive system that can counteract this powerful threat.

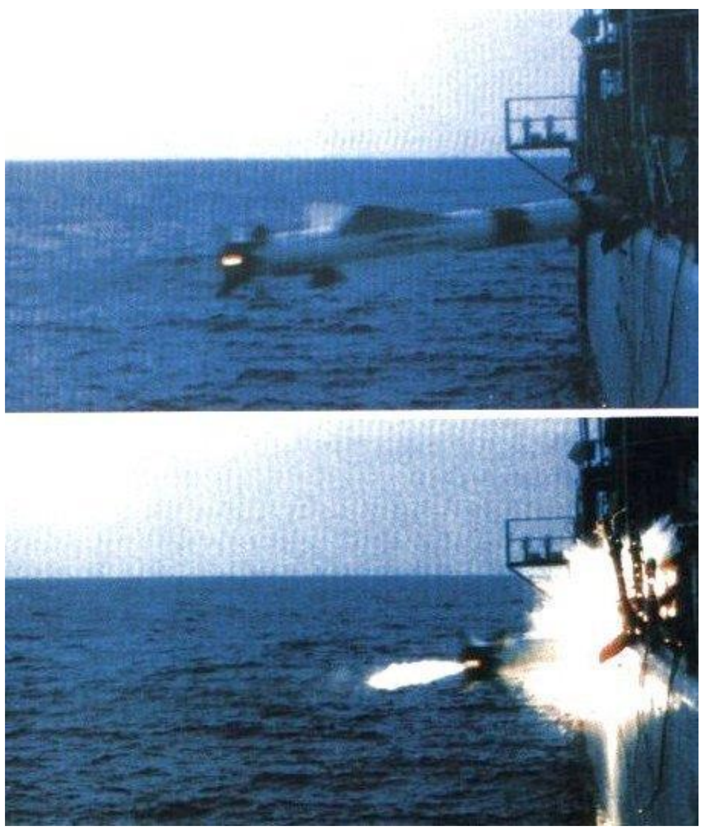
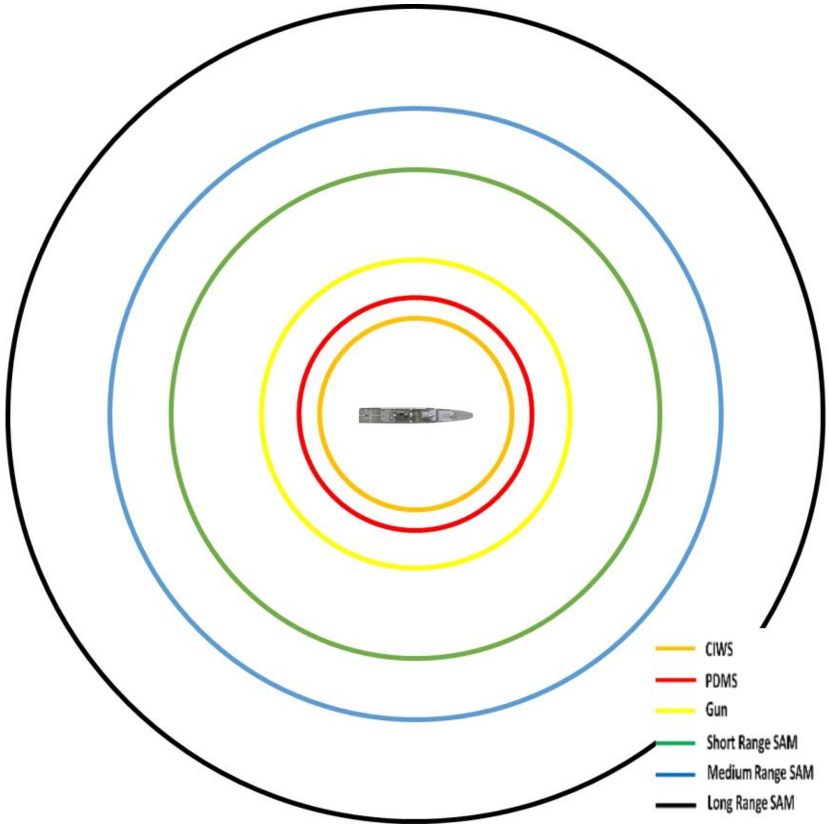


Figure 4. Exocet Finds Its Target During the Falklands War. Source: Pagi (2016).

Depending on the speed and flight paths of incoming missiles, defending ships have different time windows in which to acquire the incoming missile on their radar and engage it. For example, a missile which uses a sea skimming approach cannot be detected until it is 20–40 seconds from impact *(Defencyclopedia*, 2014).

To defend itself from any incoming ASM, a warship is developed with multiple layers of air defenses (Figure-5). This allows engagement of an inbound threat by more than one weapon system. Layered air defense usually consists of a combination of:

- Long range surface-to-air missile (SAM)
- Medium range SAM
- Short range SAM
- Medium caliber gun
- Point Defense Missile System (PDMS)
- Small caliber gun with a high rate of fire (Close-in Weapon System - CIWS)
- Electronic jamming and countermeasures
- Passive countermeasures like chaff and flares (Defencyclopedia, 2014)



Layered Air Defense allows engagement of enemy threats at multiple ranges and by more than one defensive system.

Figure 5. Layered Air Defense.

B. SHIP-BASED UNMANNED AERIAL VEHICLES

In this decade unmanned systems are very common in almost every environment. They provide new and enhanced capabilities to the warfighter (U.S. Department of Defense, 2013).

Modern navies need to conduct airborne intelligence, surveillance, and reconnaissance (ISR) anywhere and anytime (Patt, n.d.). The report also describes that current technologies have their limitations. For example, helicopters have limited range and flight time. Fixed-wing manned and unmanned aircraft have longer range but require longer runways, such as those on aircraft carriers or at land bases.

To help overcome these challenges world navies try to develop unmanned aerial vehicles that can be stationed onboard warships, such as littoral combat ships, frigates, and destroyers. As an example, the U.S. Department of Defense recently launched the Tactically Exploited Reconnaissance Node (TERN) program in 2014 to fill this need (Patt, n.d.). This aerial system will be capable of conducting UAV operations from most ship types and in rough sea conditions without extensive ship modifications.

C. AGENT-BASED SIMULATIONS

"Agent-based simulations are models where agents, objects, or entities sense and stochastically respond autonomously to conditions in their local environments" (Sanchez & Lucas, 2002). We use agent-based models to assess the effects of these individual agents' actions and interactions on the system. In agent-based models agents behave autonomously according to predefined rules.

Agent-based models have various areas of application, including military applications. Decision-making processes and training plans can be improved by using agent-based models. Furthermore, we can test tactics and war principles to determine better force structures, decide the best mix of weapons, or improve the procurement process (Cioppa, 2003).

There are many agent-based modeling tools for military applications. Several of these toolkits are BactoWars, EINSTein, MASON, NetLogo, Repast, Swarm, WISDOM, and MANA (Figure 6). MANA is selected for this research because of its effective use in many past naval studies with similar research aims.

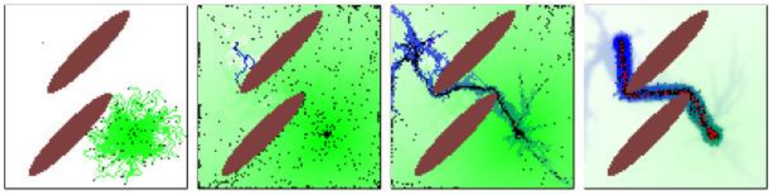


Figure 6. Agent-Based Simulation of Foraging Sequence for Ants Using MASON Simulation Toolkit. Source: Luke, Cioffi-Revilla, Panait, Sullivan, & Balan (2016).

D. MAP AWARE NON-UNIFORM AUTOMATA (MANA)

Developed by the Defence Technology Agency in New Zealand, MANA Version V is used in this thesis as a simulation platform. MANA is a time-stepped, stochastic, agent-based simulation tool designed for simulating real life military scenarios (G. McIntosh, 2009). (See Figure 7).

MANA is easy to use and offers a straightforward interface for setting battle parameters (Berryman, 2008). MANA tries to capture the essence of the physical and behavioral aspects of the scenario, but it avoids unnecessary details (e.g., detailed flight paths of missiles). In MANA, a basic military scenario can be built quickly. After creating a basic model one can change the agent's parameters and characteristics to make the scenario more accurate and realistic.

Figure 7. MANA Startup Screen.

The primary element of MANA models is the squad. A squad can consist of one or more homogeneous agents. Agents in MANA are map-aware, which means they can sense the characteristics of the environment through organic sensors or inorganic sensors (e.g., communication with other agents). Each agent has different properties. Each agent behaves independently according to the environment and the user defined rules.

Each agent in MANA has behavioral characteristics that determine its propensity to move toward or away from particular objects or agents, such as enemy aircraft in AAW missions or a high value unit in military convoy operations. Users can change these settings in the squad properties window (G. McIntosh, 2007) (Figure 8).

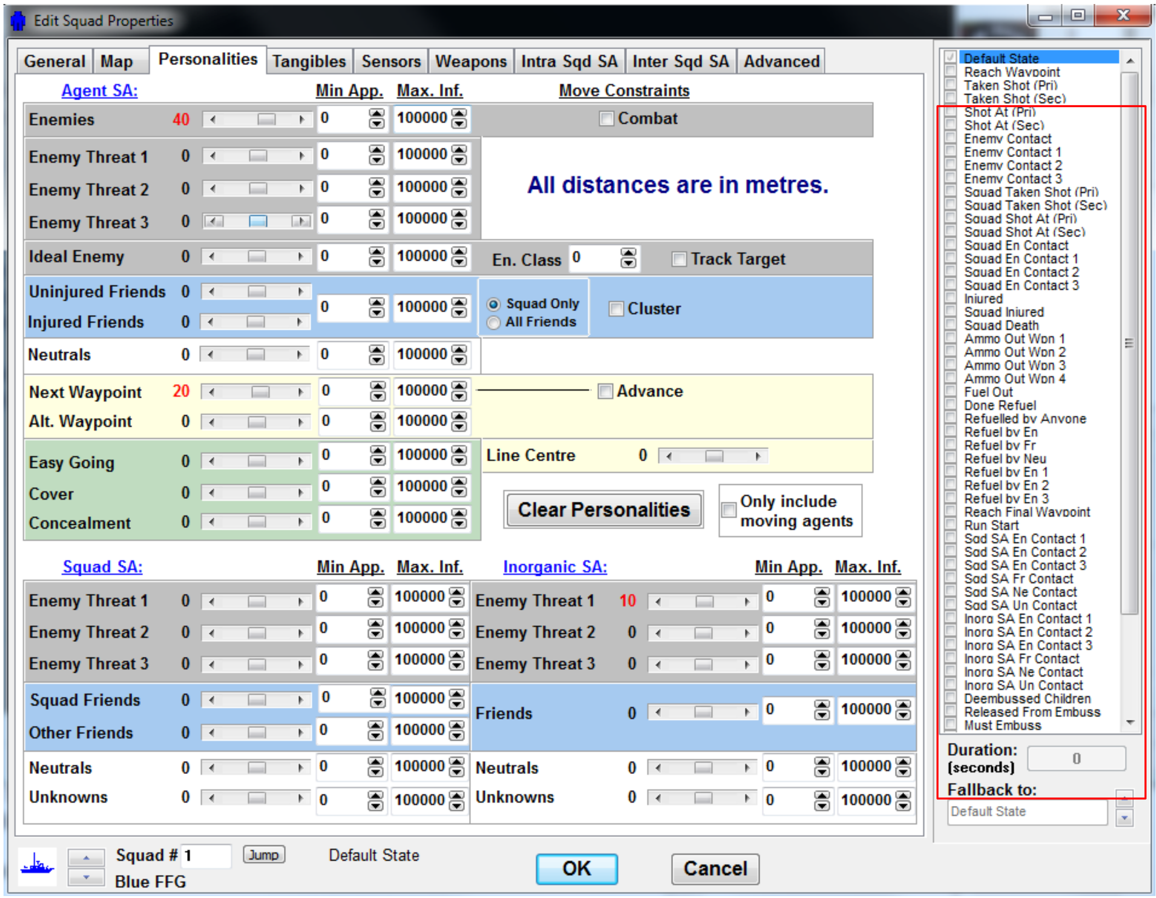


Figure 8. Squad Personalities Settings in MANA.

MANA also offers predefined states, as shown on the right side of the screenshot in Figure 8 (e.g., enemy contact, injured, or out of fuel) and a user can define different personality settings for each state.

Besides behavioral characteristics, each agent has physical characteristics. For instance, each agent has sensors, weapons, communication links between each other, speed, personal concealment, etc. An agent can detect and classify other agents within range of its sensors and can shoot classified enemy agents using its weapons (Figure 9). The personal concealment factor of an agent is used to simulate the stealth capability of an agent.

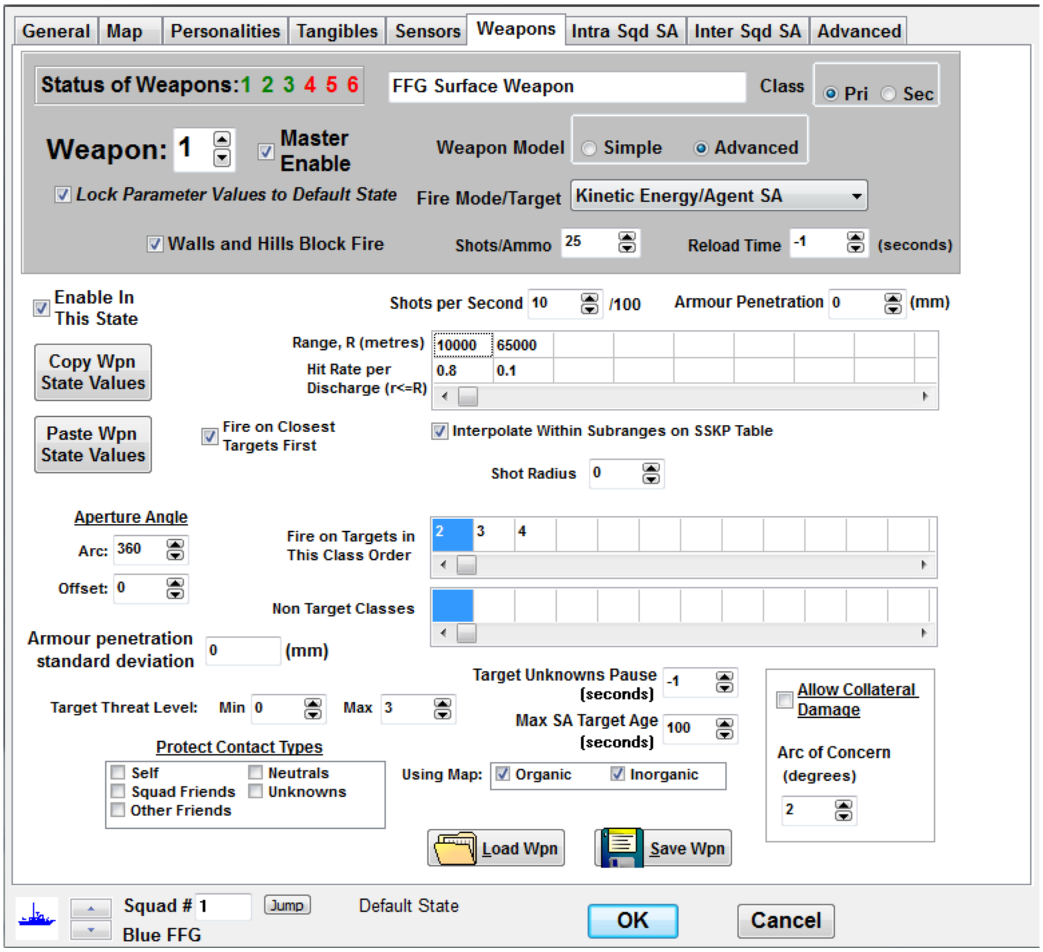


Figure 9. Weapon Settings in MANA.

Another powerful aspect of MANA is that agents can share situational awareness through communication links. Users can determine the characteristics of these communication links, such as range, reliability, delivery method (guaranteed delivery or fire and forget), and communication link latency (G. McIntosh, 2007).

MANA is a commonly used simulation tool at the Naval Postgraduate School (NPS), and it has been widely used for both military and academic studies by NPS faculty and students. Past studies similar to our approach include UAV contributions to expeditionary operations (Raffetto, 2004), counter-piracy operations in the Gulf of Aden (Tsilis, 2011), operational effectiveness of a small surface combat ship in an anti-surface warfare environment (Kaymal, 2013), and effectiveness of unmanned surface vehicles in anti-submarine warfare (Unlu, 2015). In this study MANA is used in a similar manner for simulating tactical situations, but unlike the studies mentioned previously, the focus is an AAW environment. In addition, the purpose of this study is to inform ship design, not necessarily specific tactical employment of systems or people.

III. MODEL DEVELOPMENT

A. SCENARIO DESCRIPTION

In this thesis the agent-based combat modeling tool MANA is used to simulate a single frigate in an anti-air warfare environment.

In the scenario there is one friendly AAW frigate, and it has one UAV onboard. The frigate is attacked by both land based anti-ship cruise missiles (ASMs) and air-to-surface ASMs launched by enemy aircraft. The frigate uses its layered air defense system to protect against these enemy assets. A screenshot of the scenario from MANA appears in Figure 10.

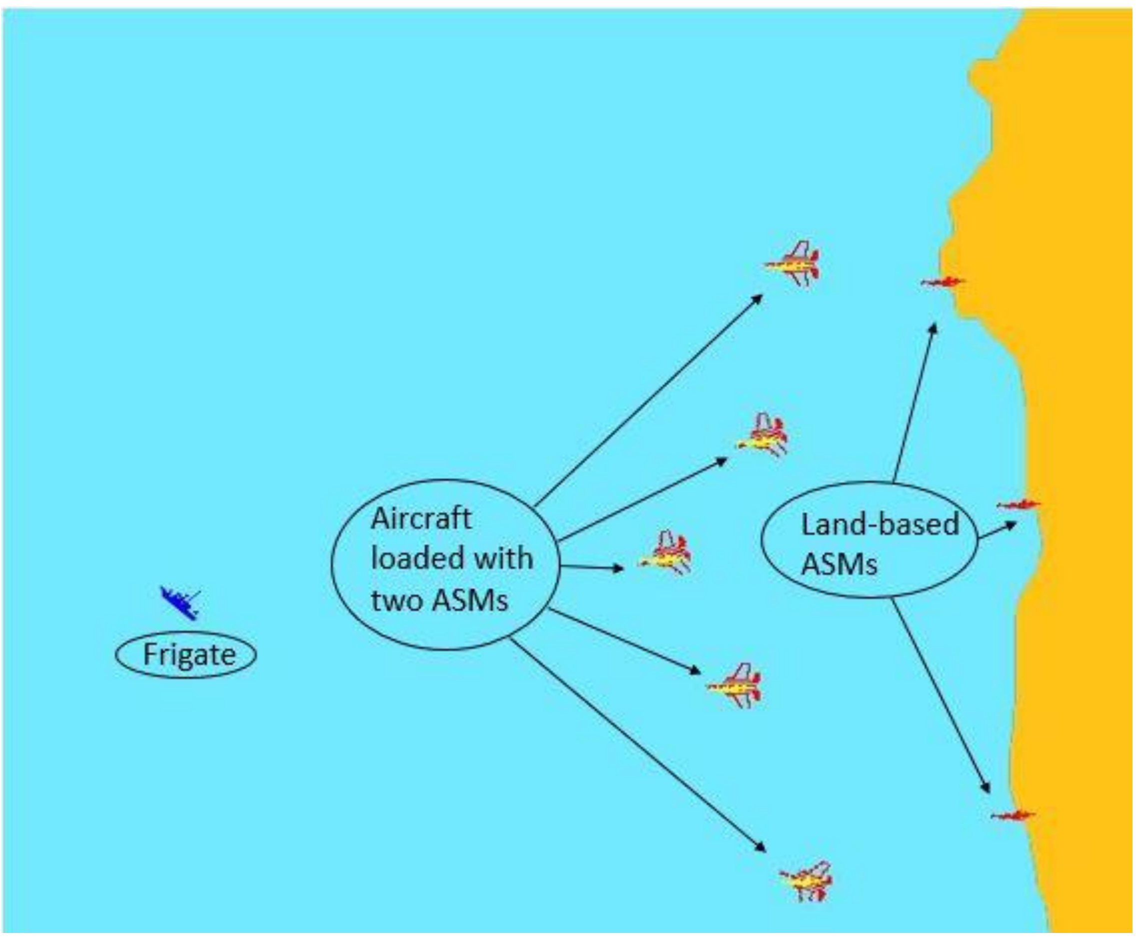


Figure 10. Screenshot of the Tactical Scenario.

The battlefield is 150 × 100 nautical miles (nm). In the MANA scenario (Figure 10), the blue colored area represents the sea and the yellow colored area is land.

B. AGENT DESCRIPTIONS

There are five different types of agents in the scenario. A frigate and a UAV onboard the frigate are friendly assets. Enemy assets are land-based ASMs, aircraft, and air-to-surface ASMs launched by the aircraft.

1. Friendly Assets

Friendly assets are trying to defend themselves while conducting an ISR mission in the area of interest. The UAV shares its situational awareness with the frigate through a directed data link.

a. Frigate

In this scenario the AAW frigate moves in a predetermined course with a speed of 25 knots (kts). The frigate has sensors and weapons to detect and neutralize enemy assets. If the frigate detects any enemy agent, it changes course to close with them.

There are two types of sensors onboard the frigate. One of them is a general purpose air-search radar, which is used to detect aircraft. The other is a missile-search radar, which is good at detecting relatively small targets but has shorter range. Table 1 summarizes the characteristics of these radars.

Table 1. Characteristics of Sensors Onboard the Frigate.

Radar	**Range**	**Target Type**
Air search radar	53,000* m	Aircraft
Missile search radar	25,000 m	Missiles

*Air search radar range is changed in the design to find the best design range.

The frigate's layered defense is limited to four weapon systems due to space restriction. A gun system is always preferred to be onboard. The other three weapon systems consist of two surface-to-air missile systems (SAMs) and either a Close-in Weapon System Gatling gun (CIWS) or a Point Defense Missile System (PDMS). These three weapon systems are changed in the experimental design to determine the best mix of weapon types for an AAW frigate in this tactical scenario. Table 2 summarizes the weapon types and their specifications. P(Hit) represents the probability of hit and MANA interpolates this value for any distance between the maximum and minimum range.

Table 2. Weapon Types and Specifications.

Weapon	**Minimum Range / P (Hit)**	**Maximum Range / P (Hit)**	**Target Type**
CIWS	1,000 m / 0.6	6,000 m / 0.4	Only missiles
PDMS	1,000 m / 0.8	9,000 m / 0.6	Only missiles
Gun	8,000 m / 0.3	14,000 m / 0.2	Both aircraft and missiles
Short Range SAM	5,000 m / 0.8	30,000 m / 0.3	Both aircraft and missiles
Medium Range SAM	10,000 m / 0.8	70,000 m / 0.1	Both aircraft and missiles
Long Range SAM	10,000 m / 0.8	200,000 m / 0.1	Both aircraft and missiles

For simulation and experimental design purposes, we categorize SAM and CIWS/PDMS alternatives into options. Table 3 depicts the mapping between the option number and the actual weapon names in that option. Again, a main gun system is present for every option.

Table 3. Weapon Selection Options.

SAM Options	Active SAM Names
1	Medium Range SAM & Short Range SAM
2	Long Range SAM & Short Range SAM
3	Long Range SAM & Medium Range SAM
CIWS/PDMS Options	**Active Weapon (CIWS or PDMS)**
1	CIWS
2	PDMS

b. Ship-based UAV

The ship-based UAV's aim is to provide early warning for the frigate via a data link. The UAV flies in a predetermined course and tries to detect enemy assets with its cookie-cutter sensor, which has range of 60,000 meters. A cookie-cutter sensor means that it detects any target within its range with certainty (Figure 11). The UAV does not have any weapon. For each tactical situation simulated with a UAV, the aircraft is assumed airborne at the time of the attack. We did not assign an on station time for the UAV because each attack takes at most 30 minutes. Table 4 summarizes the capabilities of the UAV.

Table 4. UAV Capabilities.

Sensor	**Weapon**	**Speed**	**Data Link**
Cookie cutter 60,000 m	Not Applicable	150 kts	Yes. 360,000 m

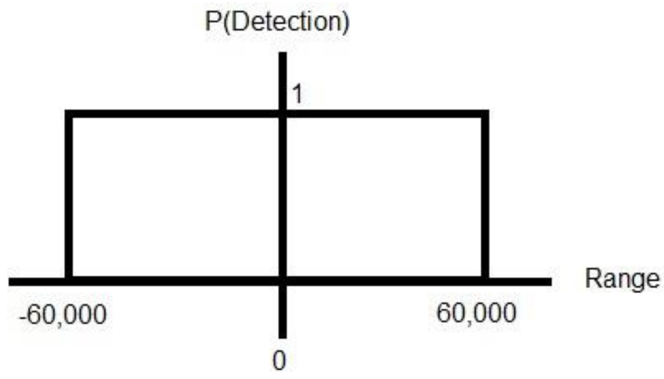


Figure 11. Graphical Explanation of a Cookie-Cutter Sensor.

2. Enemy Assets

Enemy assets consist of land-based ASMs, aircraft, and air-to-surface ASMs launched by aircraft.

a. Land-based ASMs

Land-based ASMs proceed directly to the target frigate using their inertial navigation system and active radar. They explode within 100 meters of the target. The specifications of the ASMs are as shown in Table 5.

Table 5. Land-based ASMs Specifications.

Enemy Name	**Range**	**Speed**	**Guidance System**
Land-based ASM	180 nm	1,800 kts	Active Radar Homing

b. Aircraft

Aircraft are each equipped with two air-to-surface ASMs. They launch both missiles when the friendly AAW frigate is in range of their weapon. After firing their missiles, they fly back to their base to avoid any possible enemy fire. We do not determine flight time limits for the aircraft because the tactical simulation takes only 30 minutes and is close to shore, well within the range of most tactical aircraft. Specifications of the enemy aircraft are as shown in Table 6.

Table 6. Enemy Aircrafts Specifications.

Enemy Name	Sensors	Weapons	Speed
Aircraft	Cookie-cutter 50,000 m	2 air-to-surface ASMs	300 kts

c. Air-to-Surface ASMs

ASM missiles are launched from enemy aircraft and have an active radar guidance system. They fly directly to the target with a speed of 1,800 knots. They explode when they reach 500 meters of the target. Specifications of the air-to-surface missiles appear in Table 7.

Table 7. Enemy Air-to-Surface ASMs Specifications.

Enemy Name	Range	Speed	Guidance System
Air-to-Surface ASMs	50,000 m	1,800 kts.	Active Radar Homing

C. STOP CONDITIONS

In MANA, stop conditions cause the simulation to terminate in order to reduce run time and save overall experiment time (Figure 12). The tactical simulation for our model will stop when either or both of the following conditions occur:

- The friendly frigate is killed.
- All enemy assets are neutralized by the friendly frigate.

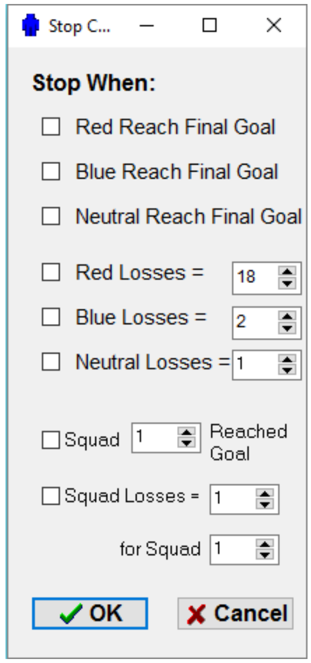


Figure 12. Stop Conditions Menu in MANA.

D. SCENARIO ASSUMPTIONS AND LIMITATIONS

Any simulation includes assumptions and limitations because it is impossible to imitate exact real-world events. These assumptions and limitations, however, need to be plausible to provide useful insights about the real world.

1. Assumptions and Constraints

The key assumptions and constraints for this analysis are:

- Only air threats are taken into account.
- Aircraft fly back to their base as soon as they launch missiles.
- Logistics are not considered (no reload of weapons for each side).
- Two missiles are loaded on each enemy aircraft.
- Space in the frigate design limits the number of AAW defense systems to three (besides medium caliber gun). Soft kill methods are neglected (electronic jamming, chaff, and flares).
- UAV shares its situational awareness with the frigate.

2. Limitations

Limitations are related to the modeling platform, MANA, and the unclassified information sources.

- Performance characteristics of radars and weapons are derived from open internet sources. Therefore, they are not exact.
- Many features of aerial platforms and weapons are not included in MANA. For example:
    1. An actual weaving flight path of a misslie cannot be simulated.
    2. Probability of detection does not differ according to the aircraft or missile's altitude.

E. MEASURE OF EFFECTIVENESS

Survivability of friendly frigate and the number of red casualties are the measures of effectiveness (MOEs) in this study. In this analysis, the frigate survives if it is hit two or fewer times. If the frigate survives after all enemy attacks, it is a success. If the frigate is shot three or more times and killed, it is a failure.

For the second MOE we focus on the number of enemy casualties, either aircraft or missile.

IV. MODEL EXPLORATION

A. DESIGN OF EXPERIMENTS

The design of experiment (DOE) is a technique to examine the relationships between design factors and outcomes. Design factors are the inputs to the simulation, and the outcomes are the two MOEs.

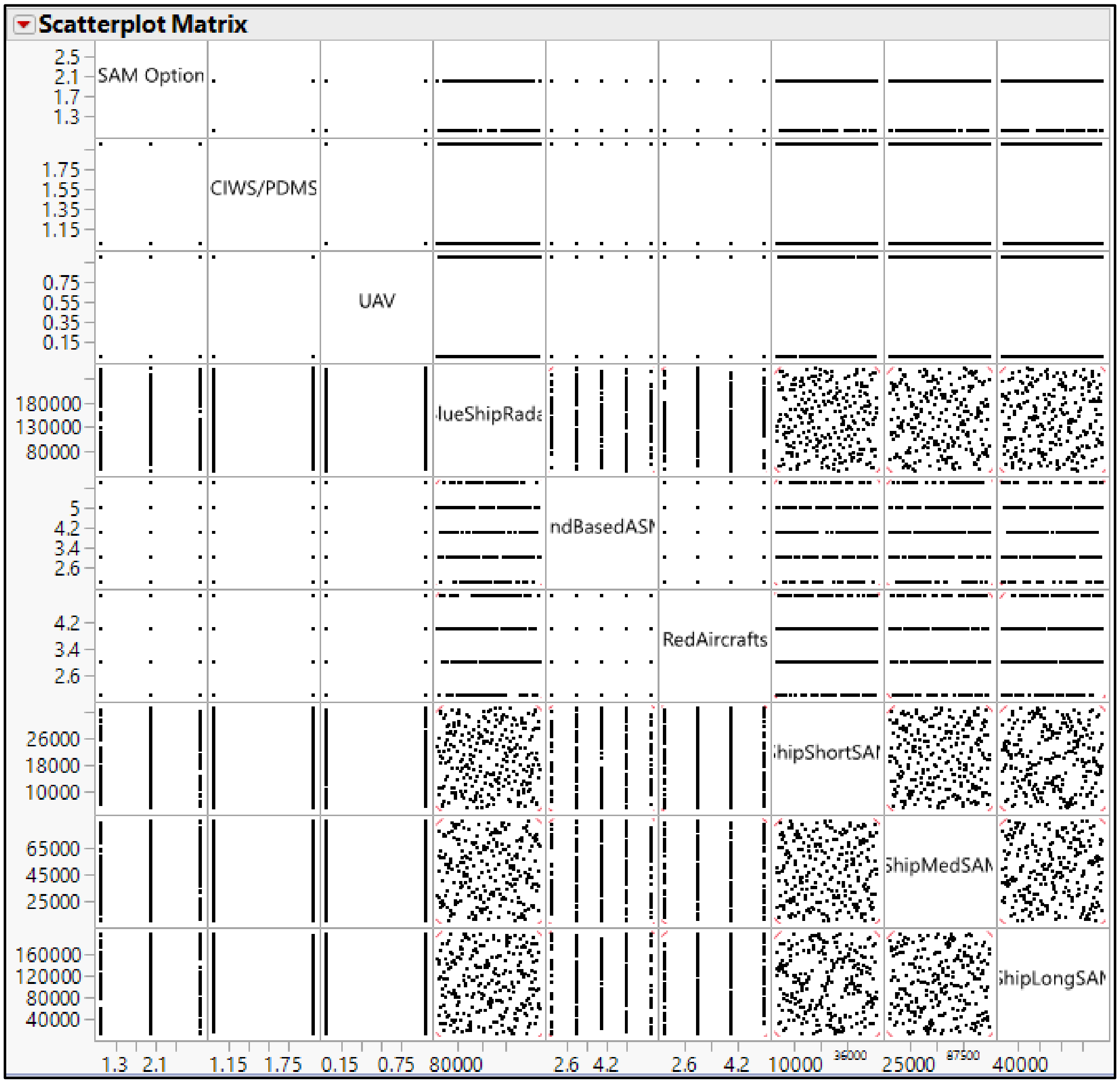
To create a simulation of military operations, the designer must consider many factors that affect the outcome. These factors can be controllable or uncontrollable. For example, weapon selection onboard a frigate is a controllable factor, but the number of enemy aircraft is an uncontrollable factor.

In this thesis' experimental design, there are seven controllable and two uncontrollable factors. These factors are discussed in the subsequent section. The nearly orthogonal Latin hypercube (NOLH) spreadsheet is used to generate design points in this analysis (Sanchez, 2011). NOLH designs have good space-filling properties, and they are almost orthogonal (Cioppa & Lucas, 2007). For example, the maximum correlation between the columns in our design matrix used in this thesis is 0.0659 (Figure 13). The scatterplot matrix of the NOLH design we used appears in Figure 14. For greater flexibility in generating NOLHs, see Hernandez et al. 2012.

Correlations

	SAM Option	CIWS/PDMS	UAV	BlueShipRadar	LandBasedASMs	RedAircrafts	BlueShipShortSAMRng	BlueShipMedSAMRng	BlueShipLongSAMRng
SAM Option	1.0000	0.0165	0.0274	0.0078	-0.0403	0.0029	0.0481	-0.0030	-0.0625
CIWS/PDMS	0.0165	1.0000	0.0039	0.0608	-0.0064	-0.0061	0.0478	0.0151	-0.0157
UAV	0.0274	0.0039	1.0000	-0.0556	-0.0064	0.0101	0.0090	-0.0531	-0.0203
BlueShipRadar	0.0078	0.0608	-0.0556	1.0000	0.0207	0.0291	0.0000	0.0000	0.0005
LandBasedASMs	-0.0403	-0.0064	-0.0064	0.0207	1.0000	-0.0496	-0.0087	0.0093	-0.0196
RedAircrafts	0.0029	-0.0061	0.0101	0.0291	-0.0496	1.0000	-0.0233	-0.0586	0.0659
BlueShipShortSAMRng	0.0481	0.0478	0.0090	0.0000	-0.0087	-0.0233	1.0000	-0.0000	0.0015
BlueShipMedSAMRng	-0.0030	0.0151	-0.0531	0.0000	0.0093	-0.0586	-0.0000	1.0000	0.0009
BlueShipLongSAMRng	-0.0625	-0.0157	-0.0203	0.0005	-0.0196	0.0659	0.0015	0.0009	1.0000

Figure 13. Correlation Matrix of the Factors.



The space filling property of the NOLH design can be easily seen in the above plot.

Figure 14. Scatterplot Matrix for the Factors.

B. DESIGN FACTORS

Many factors can affect an AAW operation. In the simulation, a total of nine factors were varied to determine the best combination of weapons. A list of factors and their explanation is shown in Table 8. These factors are explained in the subsequent sections as well.

Table 8. Design Factors.

Factor Name	Explanation	Min	Max	Unit
Controllable Factors				
SAM Option	Selection of surface to air missiles onboard	*Refer to Table 3*		
CIWS/PDMS	Selection of either CIWS or PDMS	*Refer to Table 3*		
UAV	Presence of UAV	0	1	-
BlueShipRadar	Range of the frigate's air search radar	40,000	250,000	meter
BlueShipShortSAMRng	Range of the frigate's Short range SAM	5,000	35,000	meter
BlueShipMedSAMRng	Range of the frigate's Short range SAM	10,000	85,000	meter
BlueShipLongSAMRng	Range of the frigate's Short range SAM	10,000	200,000	meter
Uncontrollable Factors				
LandBasedASMs	Number of enemy land based anti-ship missiles	2	6	-
RedAircraft	Number of enemy aircraft (each carrying two ASMs)	2	5	-

1. Controllable Factors

Controllable factors can be determined during the ship design process of the frigate. In this thesis, selection of the SAM types onboard, CIWS or PDMS selection, presence of UAV and range of the sensors and the SAMs are controllable factors.

a. Surface-to-Air Missile Options

As mentioned earlier, we divided SAMs into three groups: short range SAM, medium range SAM, and long range SAM. Due to the space restriction in the frigate, we employ two SAM types at a time. The possible selections of these two missile types and number of available missiles onbaord are as shown in Table 9.

Table 9. Possible Selection of SAMs

SAM Options	Active SAM Names
1	Medium Range SAM (12 missiles) & Short Range SAM (16 missiles)
2	Long Range SAM (12 missiles) & Short Range SAM (16 missiles)
3	Long Range SAM (12 missiles) & Medium Range SAM (16 missiles)

b. CIWS versus PDMS Selection

To evaluate the effectiveness of the CIWS and PDMS in an AAW mission, we introduce a factor which activates and deactivates either CIWS or PDMS onboard the frigate. In doing so, we intend to find which weapon type is superior to the other. Table 10 explains the mapping between selection number and the active weapon system.

Table 10. CIWS or PDMS Selection

CIWS/PDMS Options	Active Weapon (CIWS or PDMS)
1	CIWS (12 burst)
2	PDMS (21 missiles)

It is very easy to simulate most weapons in MANA due to its user friendly interface. Simulating rapid firing guns like CIWS, however, is not straightforward.

In MANA the weapon properties menu is designed for missiles, because it asks for a set of values for a single shot rather than a burst of fire. For example, MANA uses a number of shots per second and calculates the remaining ammunition according to this ratio. To overcome this issue we input the values of the CIWS burst capacity rather than an individual round.

c. Presence of UAV

Whether a UAV is present in the AAW scenario is a controllable factor in the experimental design. This factor can represent the capability of the frigate and it may be related to the tactics as well. Even if the frigate is capable of carrying a UAV, the commanding officer may choose not to conduct UAV operations due to the tactical situation.

d. Sensor Range

In AAW operations, the frigate has to detect and classify the enemy assets as soon as possible to defend effectively. Classification of the enemy assets is crucial in defense and depends on design characteristics of the ship's radar and time to classify once a target is detected. Therefore, the radar's range is designed to be a controllable factor in the study. It varies from 40,000 meters to 250,000 meters.

e. Surface-to-Air Missile Ranges

There are different types of SAMs in the defense industry and they differ from each other in their capabilities and costs. To see the effect of different SAMs’ ranges in an AAW engagement, this is introduced in the experiment as a controllable factor.

2. Uncontrollable Factors

Uncontrollable factors, also known as noise factors, are related to enemy capabilities or characteristics of the operational environment. In this thesis, there are two uncontrollable factors: number of enemy aircraft (loaded with two ASMs) and number of enemy land-based ASMs.

a. Enemy Aircraft

The number of enemy aircraft is a factor in the experimental design. It ranges from two to five aircraft. Each aircraft launches its ASMs individually as soon as the frigate is in range of their weapon, and each aircraft flies back to its base.

b. Enemy Land-based ASMs

The number of enemy land-based ASMs is another factor that ranges from two to six missiles.

C. DATA ANALYSIS

In this section we explain the analysis tool used, model runs, and initial analysis of the data, and then we discuss regression analysis and partition tree analysis.

1. Analysis Tool

JMP statistical discovery software offers both powerful statistics and dynamic graphics capabilities to its users. In the thesis, JMP statistical discovery software version 12.0.1 is used to analyze the data.

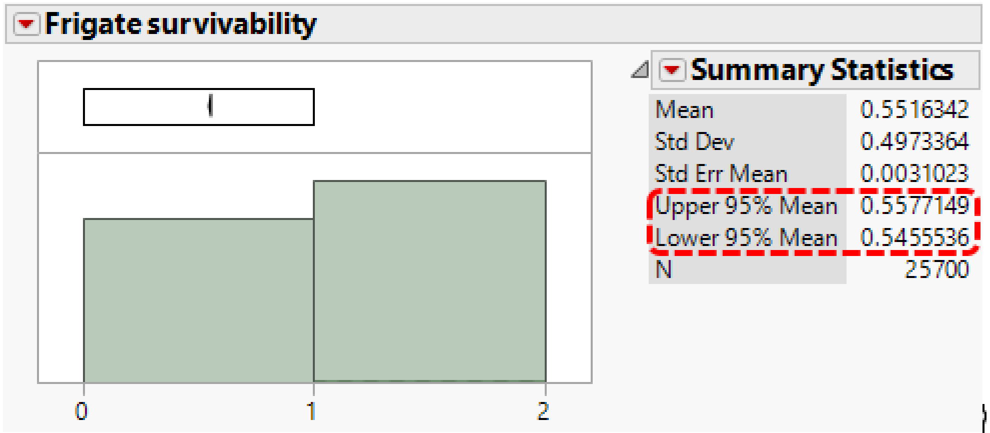
2. Model Runs

As previously indicated, nine factors are included in the model. Two hundred fifty-seven design points were generated using the NOLH design and 100 replications for each of these design points were simulated. As a result 25,700 AAW scenarios are simulated.

In this model, one second is one simulated time step. As Buss and Al Rowaei state, the time step selection has an important impact on the outcome of the model (Buss & Al Rowaei, 2010). They also explain that models with larger time steps take less time but may yield erroneous results. Therefore, time step selection should be considered thoroughly to get correct results in a reasonable time period. Because of the high speed of ASMs, a one-second time step is selected to capture the rapid nature of AAW tactics.

3. Initial Analysis of the Data

A total of 25,700 rows of raw data from the simulation experiments are imported into JMP for analysis. To explore the survivability of the frigate, we created a new column by subtracting the frigate casualty percent column from one. Figure 15 displays the distribution of the frigate's probability of survival in the overall replications. Average survivability is around 0.551, with a standard deviation of 0.497. The upper and lower 95 percent confidence interval is as shown in Figure 15.



The right bar in the figure corresponds to the proportion of the runs in which the frigate survives (55% of the time) and the left bar the proportion in which it does not (45% of the time).

Figure 15. Distribution for the Mean Frigate Survivability.

For the exploration of the second MOE, we created a distribution plot of the mean number of enemy casualties (Figure 16). As it appears in Figure 16, the mean enemy casualties has a bimodal distribution with a mean of 8.748 casualties and a standard deviation of 4.745. The distribution has two distinct peak points, in other words, two modes.

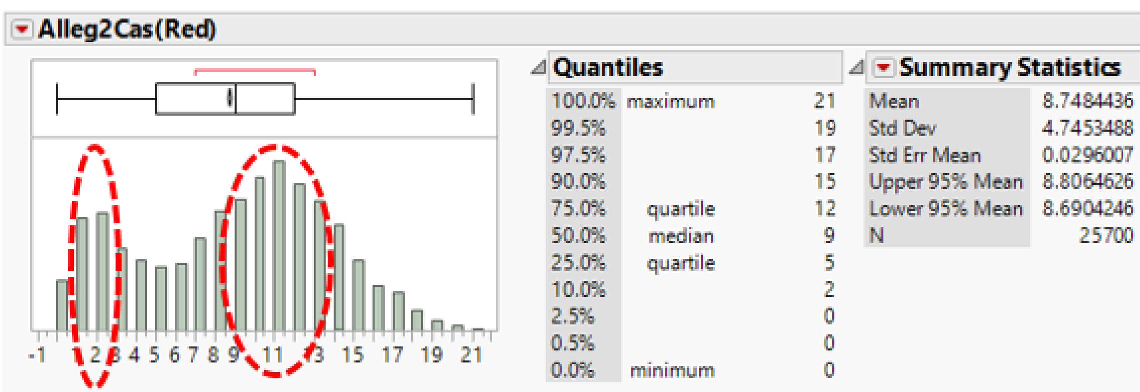


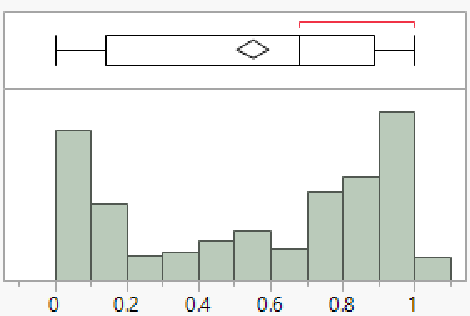
Figure 16. Distribution for the Mean Enemy Casualties Showing a Bi-modal Characteristic.

4. Regression Analysis

In our raw data there are 100 replications for each of the 257 design points. Although the input parameters stay the same across 100 replications, the outcome will vary due to stochasticity originating from the MANA modeling platform. This randomness causes difficulty in fitting the regression model. To overcome this difficulty, we summarize the data by taking the means of the factors and the response for each design point. Therefore, the survivability response becomes the probability of survivability ranging from zero to one, and the number of enemy casualties becomes the mean number of enemy casualties ranging from zero to 19. They are now both continuous variables.

Distributions of the frigate's survivability and the enemy casualties for the summarized data are as shown on Figure 17 and Figure 18. We should note that the summary statistics are the same as the previous distributions.

Mean(Frigate survivability)



Quantiles

100.0%	maximum	1
99.5%		1
97.5%		1
90.0%		0.97
75.0%	quartile	0.89
50.0%	median	0.68
25.0%	quartile	0.14
10.0%		0.018
2.5%		0
0.5%		0
0.0%	minimum	0

Summary Statistics

Mean	0.5516342
Std Dev	0.3643236
Std Err Mean	0.0227259
Upper 95% Mean	0.5963877
Lower 95% Mean	0.5068808
N	257

Figure 17. Distribution for the Mean Frigate Survivability (summarized data).

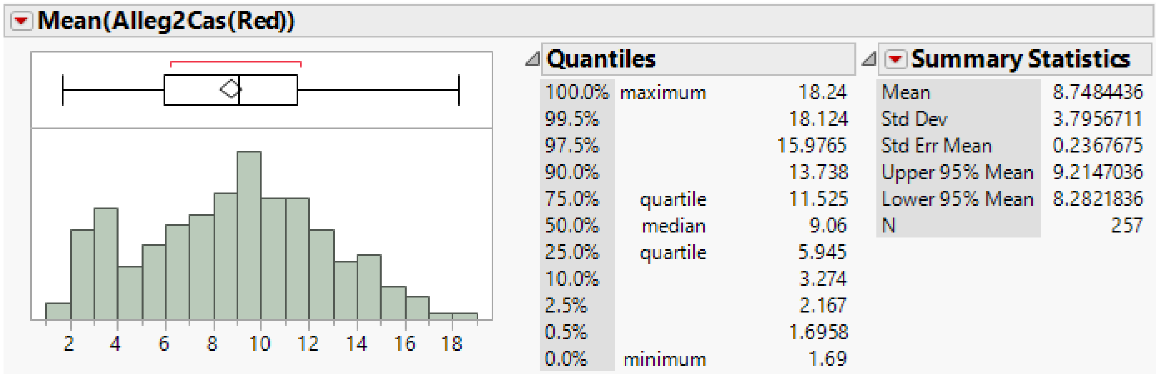


Figure 18. Distribution for the Mean Enemy Casualties (Summarized Data).

We use regression analysis to investigate the relationships between the design factors and our MOEs. There are many techniques for regression analysis; the corrected Akeike Information Criterion (AICc) stepwise technique is used in this study.

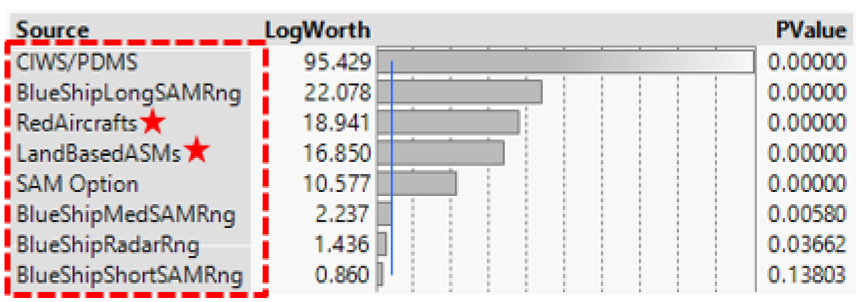
We first fit the model with only main effect terms, then we add a second order polynomial and two-way interaction terms into the model to investigate their value as predictors.

We need to note that, due to the binary responses, the basic assumptions for linear regression are not met. Specifically, the errors will not be normally distributed with a constant variance. In addition, the regression equation may make predictions less than zero or more than one at the extremes, while the response must be restricted to between zero and one.

However, the purpose of our analysis is to identify and quantify the relationship between the input variables and the response rather than predicting the response (Kleijnen et al. 2005). As noted by Hellevik (2009), “the intuitively meaningful interpretation of linear regression makes it easier to communicate research results than logistic regression.” The p-values cannot be reliably used because the error terms are not normally distributed. The coefficient estimates are not optimal in terms of power, but they are unbiased. Moreover, optimal power is not a critical issue given our large sample and high R-square value. For more discussion on this, see Hellevik (2009).

a. Main Effects Model for the Frigate Survivability

Using the stepwise method with only main effect terms we defined the best predictors as shown in Figure 19. The factors are listed in order according to their effects on the response. For example, the effect of the CIWS/PDMS selection on survivability is greater than the range of the radars. We should also note the two uncontrollable factors of number of red aircraft and land launched ASCMs are in the model. The UAV factor, though, is not included in the model as a significant predictor of survivability.

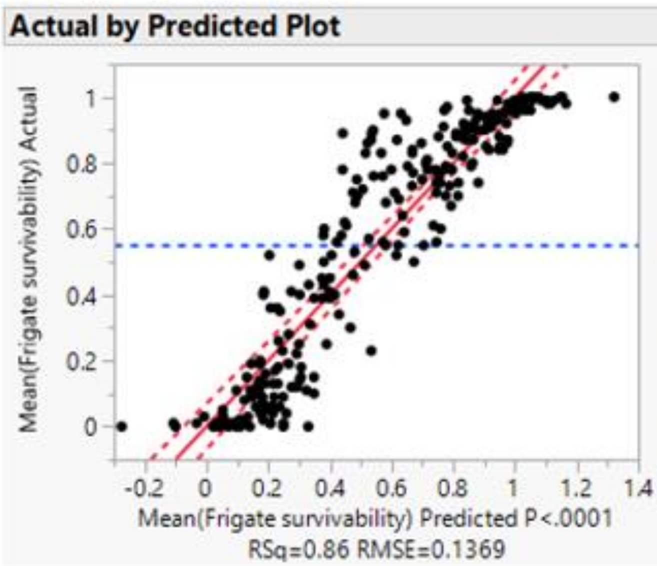


Source	LogWorth	PValue
CIWS/PDMS	95.429	0.00000
BlueShipLongSAMRng	22.078	0.00000
RedAircrafts★	18.941	0.00000
LandBasedASMs★	16.850	0.00000
SAM Option	10.577	0.00000
BlueShipMedSAMRng	2.237	0.00580
BlueShipRadarRng	1.436	0.03662
BlueShipShortSAMRng	0.860	0.13803

★ Uncontrollable factors

Figure 19. Effect Summary of the Factors for Main Effects Model.

Figure 20 displays the actual values by predicted values and summary of the fitted model. As mentioned earlier, the UAV factor is excluded from the model, because it is not significant enough to enter the model. The R-Square value of the model is 0.857, which means our model can explain 85.7 percent of the variability of the response.



Summary of Fit

RSquare	0.863673
RSquare Adj	0.858706
Root Mean Square Error	0.136946
Mean of Response	0.551634
Observations (or Sum Wgts)	257

Figure 20. Actual by Predicted Plot and the Summary of Fit for the Main Effects Model.

Figure 21 displays the expanded parameter estimates for the main effects model. The t ratio values represent the significance of the factors' effect on survivability. Factors indicated with red dashed boxes have more significant effect on survivability as compared to other factors.

Expanded Estimates

Nominal factors expanded to all levels

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	0.8066803	0.057718	13.98	<.0001*
CIWS/PDMS[1]	-0.294794	0.008572	-34.39	<.0001*
CIWS/PDMS[2]	0.2947938	0.008572	34.39	<.0001*
BlueShipRadarRng	2.9572e-7	1.407e-7	2.10	0.0366*
LandBasedASMs	-0.064224	0.00697	-9.21	<.0001*
RedAircrafts	-0.088704	0.008963	-9.90	<.0001*
BlueShipShortSAMRng	1.4659e-6	9.852e-7	1.49	0.1380
BlueShipMedSAMRng	1.0959e-6	3.938e-7	2.78	0.0058*
BlueShipLongSAMRng	1.6967e-6	1.558e-7	10.89	<.0001*
SAM Option[1]	-0.098369	0.013407	-7.34	<.0001*
SAM Option[2]	0.0369359	0.011393	3.24	0.0014*
SAM Option[3]	0.061433	0.013354	4.60	<.0001*

Figure 21. Expanded Estimates for the Main Effects Model.

As shown in the prediction expression (Figure 20), an increase in the uncontrollable factors decreases the probability of survivability. Conversely, an increase in controllable factors increases the survivability rate. Interestingly, the selection of the CIWS (CIWS/PDMS=1) and SAM Option 1 (Medium and short range SAM) decreases the probability of survival.

Prediction Expression

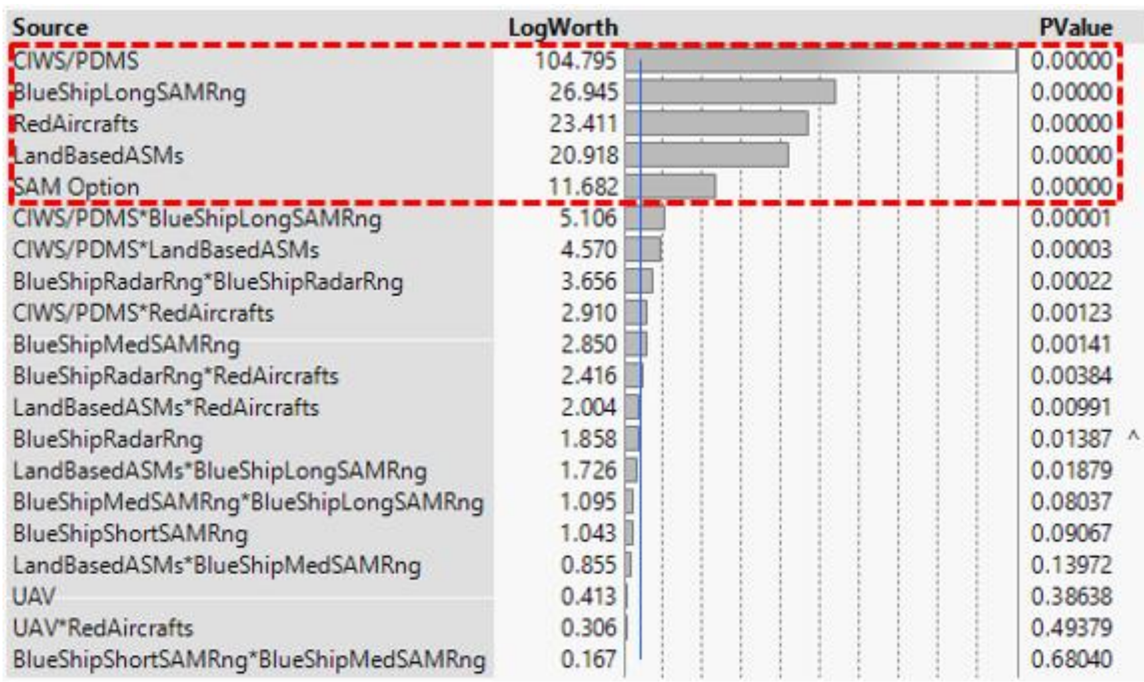
$$
\begin{aligned}
&0.80668032351503 \\
&+ \text{Match}\left(\text{CIWS/PDMS}\right)\begin{bmatrix} 1 & \Rightarrow -0.2947938119832 \\ 2 & \Rightarrow 0.29479381198324 \\ \text{else} \Rightarrow . & \end{bmatrix} \\
&+ 0.00000029572071 * \text{BlueShipRadarRng} \\
&+ -0.0642238997863 * \text{LandBasedASMs} \\
&+ -0.0887042504378 * \text{RedAircrafts} \\
&+ 0.00000146588744 * \text{BlueShipShortSAMRng} \\
&+ 0.00000109588815 * \text{BlueShipMedSAMRng} \\
&+ 0.00000169667207 * \text{BlueShipLongSAMRng} \\
&+ \text{Match}\left(\text{SAM Option}\right)\begin{bmatrix} 1 & \Rightarrow -0.098368842621 \\ 2 & \Rightarrow 0.03693587998977 \\ 3 & \Rightarrow 0.06143296263125 \\ \text{else} \Rightarrow . & \end{bmatrix}
\end{aligned}
$$

Figure 22. Prediction Expression of the Main Effects Model.

As a result of this analysis, we conclude that selection of PDMS (CIWS/PDMS=2), a mix of medium and long range SAM (SAM Option=3), and longer ranges in radar and missiles are recommended for a better survivability rate.

b. Second Order Model for Frigate Survivability

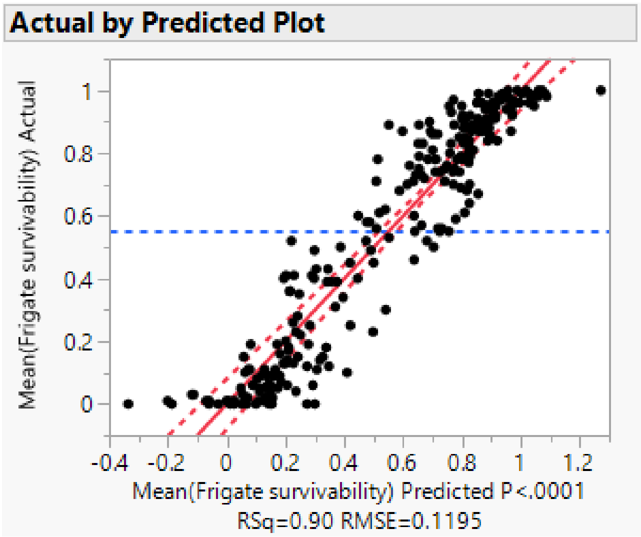
After exploring the main effects model, we fit the model with main effects, second order polynomial, and two-way interaction terms as predictors, to find their impact on the frigate's survival probability. The terms that are significant enough to enter the model appear in Figure 23. The first five significant factors are still main effects, although we added polynomials and the two-way interactions to the model.



Source	LogWorth	PValue
CIWS/PDMS	104.795	0.00000
BlueShipLongSAMRng	26.945	0.00000
RedAircrafts	23.411	0.00000
LandBasedASMs	20.918	0.00000
SAM Option	11.682	0.00000
CIWS/PDMS*BlueShipLongSAMRng	5.106	0.00001
CIWS/PDMS*LandBasedASMs	4.570	0.00003
BlueShipRadarRng*BlueShipRadarRng	3.656	0.00022
CIWS/PDMS*RedAircrafts	2.910	0.00123
BlueShipMedSAMRng	2.850	0.00141
BlueShipRadarRng*RedAircrafts	2.416	0.00384
LandBasedASMs*RedAircrafts	2.004	0.00991
BlueShipRadarRng	1.858	0.01387 ^
LandBasedASMs*BlueShipLongSAMRng	1.726	0.01879
BlueShipMedSAMRng*BlueShipLongSAMRng	1.095	0.08037
BlueShipShortSAMRng	1.043	0.09067
LandBasedASMs*BlueShipMedSAMRng	0.855	0.13972
UAV	0.413	0.38638
UAV*RedAircrafts	0.306	0.49379
BlueShipShortSAMRng*BlueShipMedSAMRng	0.167	0.68040

Figure 23. Effect Summary of the Factors for the Second Order Model.

The actual by predicted plot and the summary of fit for the second order model is as shown in Figure 24. The R-squared value of this model is .90, which means that 90 percent of the variability in the simulation can be explained using this regression model.



Summary of Fit

RSquare	0.901292
RSquare Adj	0.892472
Root Mean Square Error	0.119467
Mean of Response	0.551634
Observations (or Sum Wgts)	257

Figure 24. Actual by Predicted Plot and the Summary of Fit for the Second Order Model.

Expanded parameter estimates for the main effects model are shown in Figure 25. According to the t ratio values, the same main effect terms as in the previous model are more significant in regard to survivability as compared to the others. The two-way interactions—CIWS/PDMS × Land-based ASM and CIWS/PDMS × range of the long range SAM—are relatively significant factors compared to other two-way interactions. Interestingly, the quadratic term of the radar range has a greater effect than the main effect of the radar range. Therefore, changes in the radar range affects the frigate's survivability non-linearly.

Expanded Estimates

Nominal factors expanded to all levels

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	0.8440495	0.05131	16.45	<.0001*
CIWS/PDMS[1]	-0.294669	0.007478	-39.40	<.0001*
CIWS/PDMS[2]	0.2946688	0.007478	39.40	<.0001*
UAV[0]	-0.006491	0.00748	-0.87	0.3864
UAV[1]	0.0064911	0.00748	0.87	0.3864
BlueShipRadarRng	3.0489e-7	1.23e-7	2.48	0.0139*
LandBasedASMs	-0.064341	0.006082	-10.58	<.0001*
RedAircrafts	-0.088864	0.00782	-11.36	<.0001*
BlueShipShortSAMRng	1.4601e-6	8.595e-7	1.70	0.0907
BlueShipMedSAMRng	1.1113e-6	3.44e-7	3.23	0.0014*
BlueShipLongSAMRng	1.6933e-6	1.36e-7	12.45	<.0001*
CIWS/PDMS[1]*(LandBasedASMs-4.00778)	-0.026331	0.006148	-4.28	<.0001*
CIWS/PDMS[2]*(LandBasedASMs-4.00778)	0.0263314	0.006148	4.28	<.0001*
CIWS/PDMS[1]*(RedAircrafts-3.50195)	-0.026277	0.008031	-3.27	0.0012*
CIWS/PDMS[2]*(RedAircrafts-3.50195)	0.0262774	0.008031	3.27	0.0012*
CIWS/PDMS[1]*(BlueShipLongSAMRng-105000)	6.2485e-7	1.367e-7	4.57	<.0001*
CIWS/PDMS[2]*(BlueShipLongSAMRng-105000)	-6.249e-7	1.367e-7	-4.57	<.0001*
UAV[0]*(RedAircrafts-3.50195)	-0.005478	0.007992	-0.69	0.4938
UAV[1]*(RedAircrafts-3.50195)	0.0054776	0.007992	0.69	0.4938
(BlueShipRadarRng-145000)*(RedAircrafts-3.50195)	-4.144e-7	1.419e-7	-2.92	0.0038*
(LandBasedASMs-4.00778)*(RedAircrafts-3.50195)	0.0180938	0.006959	2.60	0.0099*
(LandBasedASMs-4.00778)*(BlueShipMedSAMRng-47500)	4.4475e-7	3.001e-7	1.48	0.1397
(LandBasedASMs-4.00778)*(BlueShipLongSAMRng-105000)	-2.422e-7	1.024e-7	-2.37	0.0188*
(BlueShipShortSAMRng-20000)*(BlueShipMedSAMRng-47500)	-1.67e-11	4.06e-11	-0.41	0.6804
(BlueShipMedSAMRng-47500)*(BlueShipLongSAMRng-105000)	-1.18e-11	6.7e-12	-1.76	0.0804
(BlueShipRadarRng-145000)*(BlueShipRadarRng-145000)	-9.14e-12	2.44e-12	-3.75	0.0002*
SAM Option[1]	-0.091086	0.0119	-7.65	<.0001*
SAM Option[2]	0.0248864	0.010801	2.30	0.0221*
SAM Option[3]	0.0661996	0.011839	5.59	<.0001*

Figure 25. Expanded Estimates for the Second Order Model.

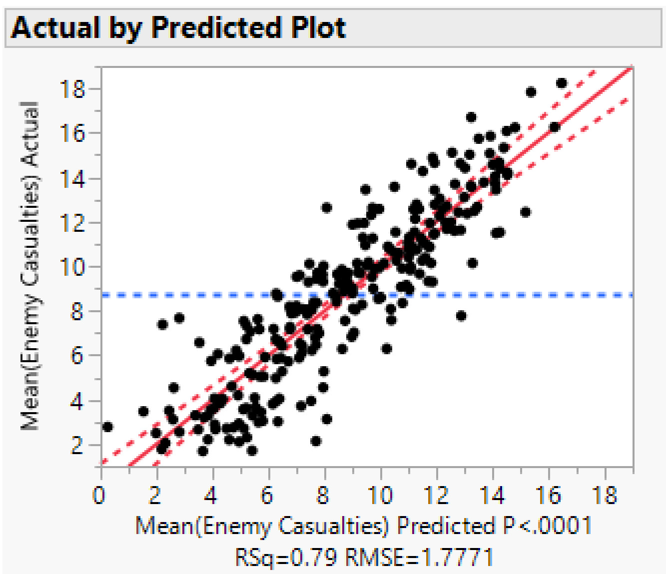
c. Main Effects Model for the Number of Enemy Casualties

Using the stepwise regression technique with AICc criterion, the factors shown in Figure 26 are significant enough to be a predictor of the number of enemy causalities. Differing from the main effects model for frigate survivability, the range of the short range SAM and number of land attack missiles are not significant predictors in this model.

Source	LogWorth	PValue
CIWS/PDMS	63.444	0.00000
BlueShipLongSAMRng	28.040	0.00000
RedAircrafts	17.037	0.00000
SAM Option	16.221	0.00000
BlueShipMedSAMRng	4.315	0.00005
BlueShipRadarRng	3.543	0.00029

Figure 26. Effect Summary of the Factors for Main Effect Model.

The actual by predicted plot and the summary of fit of the main effects model is as shown in Figure 27. The R squared value is around 0.787 for this model.



Summary of Fit

RSquare	0.786789
RSquare Adj	0.780795
Root Mean Square Error	1.777106
Mean of Response	8.748444
Observations (or Sum Wgts)	257

Figure 27. Actual by Predicted Plot and the Summary of Fit for the Main Effects Model for Enemy Casualties.

Expanded parameter estimates appear in Figure 28. According to t ratio values, CIWS/PDMS selection, range of long range SAM, SAM option ,and number of aircraft have more significant effects as compared to radar range and medium range SAM’s range.

Expanded Estimates

Nominal factors expanded to all levels

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	0.1707908	0.58806	0.29	0.7717
SAM Option[1]	-1.616312	0.173729	-9.30	<.0001*
SAM Option[2]	0.4928158	0.147833	3.33	0.0010*
SAM Option[3]	1.1234958	0.172975	6.50	<.0001*
CIWS/PDMS[1]	-2.577384	0.111108	-23.20	<.0001*
CIWS/PDMS[2]	2.5773843	0.111108	23.20	<.0001*
BlueShipRadarRng	6.7183e-6	1.826e-6	3.68	0.0003*
RedAircrafts	1.0766072	0.116137	9.27	<.0001*
BlueShipMedSAMRng	2.1133e-5	5.11e-6	4.14	<.0001*
BlueShipLongSAMRng	2.5641e-5	2.022e-6	12.68	<.0001*

Figure 28. Expanded Estimates for the Main Effects Model.

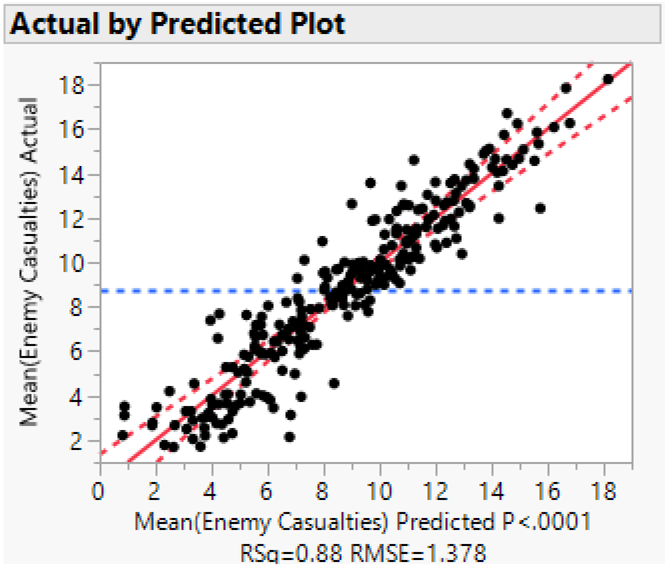
d. Second Order Model for the Number of Enemy Casualties

To evaluate the effects of two-way interactions and polynomial terms, we build the second order regression model for the number of enemy casualties using the same regression technique and AICc criterion. Predictors used in this model appear in Figure 29.

Source	LogWorth	PValue	
CIWS/PDMS	80.250	0.00000	
BlueShipLongSAMRng	39.552	0.00000	
RedAircrafts	25.317	0.00000	
SAM Option	22.992	0.00000	
CIWS/PDMS*RedAircrafts	12.558	0.00000	
CIWS/PDMS*LandBasedASMs	9.817	0.00000	
BlueShipMedSAMRng	6.439	0.00000	
BlueShipRadarRng	5.183	0.00001	
BlueShipRadarRng*BlueShipRadarRng	4.795	0.00002	
CIWS/PDMS*BlueShipLongSAMRng	3.989	0.00010	
RedAircrafts*BlueShipLongSAMRng	2.791	0.00162	
RedAircrafts*RedAircrafts	1.857	0.01389	
BlueShipRadarRng*BlueShipLongSAMRng	1.788	0.01629	
BlueShipLongSAMRng*BlueShipLongSAMRng	1.499	0.03170	
CIWS/PDMS*UAV	1.292	0.05109	
UAV	1.072	0.08470	^
CIWS/PDMS*BlueShipRadarRng	1.049	0.08935	
BlueShipMedSAMRng*BlueShipMedSAMRng	0.979	0.10487	
UAV*BlueShipRadarRng	0.735	0.18409	
BlueShipRadarRng*LandBasedASMs	0.719	0.19097	
RedAircrafts*BlueShipMedSAMRng	0.704	0.19767	
BlueShipShortSAMRng	0.590	0.25707	
LandBasedASMs	0.398	0.40019	^
BlueShipShortSAMRng*BlueShipMedSAMRng	0.157	0.69680	
BlueShipRadarRng*RedAircrafts	0.021	0.95243	

Figure 29. Effect Summary of the Factors for Second Order Model.

The R squared value is around 0.88 for the second order model. Figure 30 displays the summary of fit and actual by predict plot. As shown, CIWS/PDMS selection, range of long range SAM, number of enemy aircraft, SAM option and CIWS/PDMS × number of enemy aircraft are the five most significant factors in predicting enemy casualties.



Summary of Fit

RSquare	0.881582
RSquare Adj	0.868195
Root Mean Square Error	1.378015
Mean of Response	8.748444
Observations (or Sum Wgts)	257

Figure 30. Actual by Predicted Plot and the Summary of Fit for the Second Order Model.

5. Classification and Regression Tree

Classification and regression trees offer an easy way to examine the contribution of the factors to the outcome. Classification trees are used when the response or outcome is discrete or categorical. If the response is a continuous variable, regression trees are used. We use regression trees for analysis of the factors that affect the frigate's survival probability using the summarized data.

After building our regression tree model, we examine the candidate split point reports generated by JMP (Figure 31), which shows the LogWorth value of the factors. The split occurs according to the LogWorth statistic. For example, the CIWS/PDMS factor is the first optimal split point in the model.

Candidates			
Term	**Candidate SS**	**LogWorth**	**Cut Point**
SAM Option	1.10712788	2.1060455	1
CIWS/PDMS	22.77077263 *	113.4492899	1
UAV	0.00655945	0.0712817	0
BlueShipRadarRng	1.77272841	2.6724219	82656
LandBasedASMs	1.28775413	2.3612961	5
RedAircrafts	1.41975858	2.7843386	4
BlueShipShortSAMRng	0.54705871	0.4484654	21875
BlueShipMedSAMRng	0.77409554	0.7894175	33438
BlueShipLongSAMRng	1.84783974	2.8303513	79023

Figure 31. Candidate Split Points.

The regression tree appears in Figure 32. As stated earlier, the first split occurs with the CIWS/PDMS selection factor. If CIWS is selected in the design the survival probability becomes 0.25; however, it increases up to 0.85 if PDMS is employed.

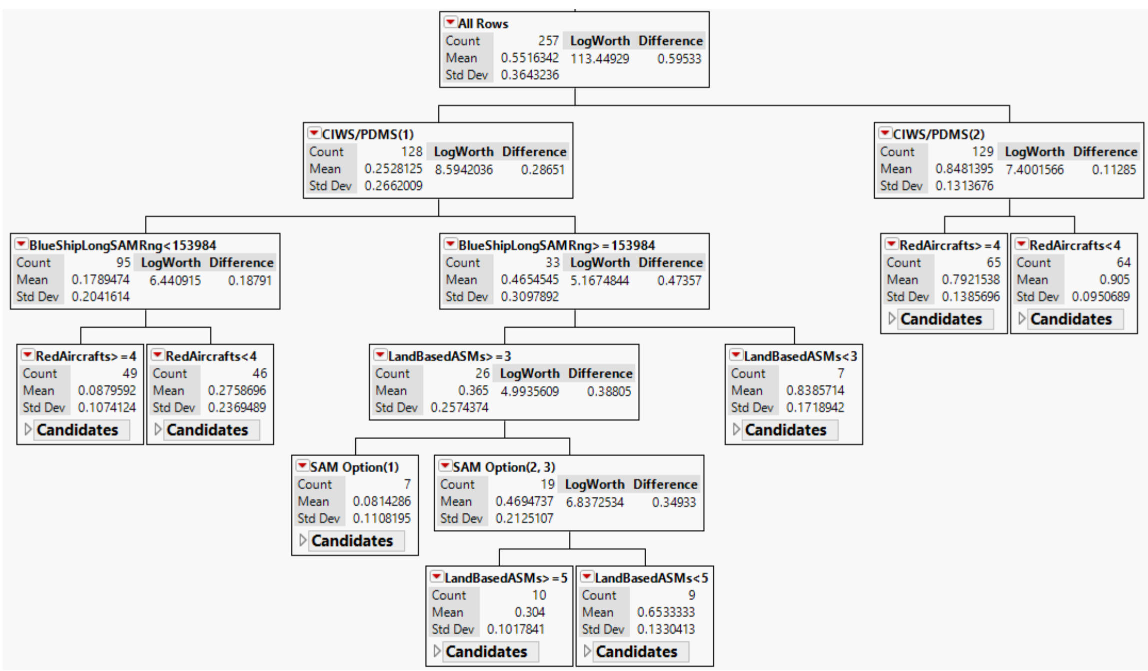


Figure 32. Regression Tree for Frigate's Survival Probability.

The second partition occurs under selection of CIWS (CIWS/PDMS=1) with the range of long range SAM. This means that if CIWS is employed and the range of the long range SAM is less than 153,984 meters, the probability of survival becomes 0.18. If the range is above 153,984, the survival probability is 0.46. It is also shown on the right leaf of the tree that if PDMS is employed and the number of aircraft is less than or equal to four, the frigate's survival rate becomes 0.90.

After seven splits we reach an R square value of 0.842. An increase in the number of splits always yields an increase in the R squared value. Furthermore, more splits cause additional complexity in the tree, and it does not contribute to the model significantly. Figure 33 displays the split history (number of splits vs. R squared value). After the seventh split, more splitting does not contribute to our model in terms of R squared value.

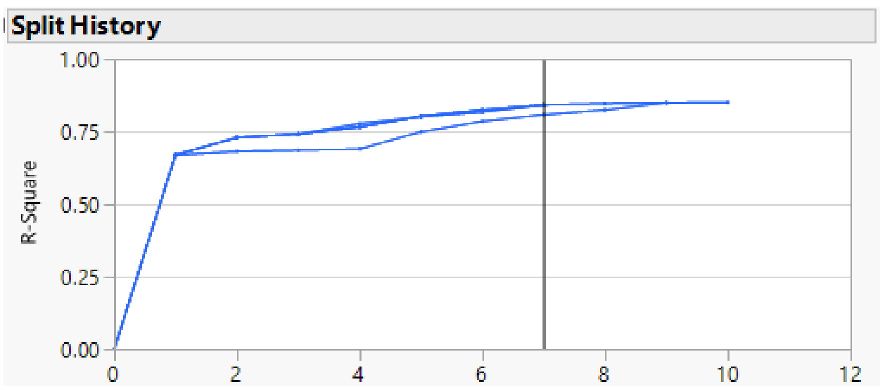


Figure 33. Split History.

To evaluate the contributions of the factors, we need to examine the column contributions report created by JMP (Figure 34). As it is easily seen in this report, the most significant five factors are the same as the previous ones.

Column Contributions

Term	Number of Splits	SS	Portion
CIWS/PDMS	1	22.7707726	0.7958
BlueShipLongSAMRng	1	2.01047458	0.0703
LandBasedASMs	2	1.8149372	0.0634
RedAircrafts	2	1.24843863	0.0436
SAM Option	1	0.77026955	0.0269
UAV	0	0	0.0000

Figure 34. Contributions of the Factors.

D. FACTOR SIGNIFICANCE

The significance of specific design factors in regard to a frigate’s survivability and the number of enemy casualties is summarized in the following subsections.

1. Factor Significance in Frigate’s Survival Probability

For the particular AAW scenario in this thesis, factors that are determined to be significant in a frigate’s survivability and their rankings are as shown in Table 11.

Table 11. Summary of the Factor Significance for a Frigate's Survival Probability.

Factor Name	Main Effects Model	Second Order Model	Regression Tree
CIWS/PDMS Selection	1	1	1
Range of Long Range SAM	2	2	2
Number of Enemy Aircraft	3	3	4
Number of Land Based ASMs	4	4	3
SAM Option	5	5	5
Range of Medium Range SAM	6	10	-
Radar Range	7	8	-
UAV	-	18	-

The selection of the CIWS/PDMS is the most significant design factor. Employment of the PDMS is superior to CIWS in terms of a frigate's survivability. This makes sense as PDMS has higher probability of hit compared to CIWS.

The range of the long range SAM is the second most significant design factor that affects the frigate's survivability. An increase in the range, increases survivability.

The third and fourth most important factors are the number of enemy aircraft and land-based ASMs. It is obvious that if the number of enemy assets increases, the survival probability of the friendly frigate decreases. These are uncontrollable factors, but they can be estimated according to the planned operational employment of the prospective frigates.

SAM option is the other factor that has a significant effect on the friendly frigate's survivability. Although SAM option 1 decreases the survivability, selection of SAM option 2 or SAM option 3 increases the survival probability.

Among all SAM options, the selection of long range and medium range SAM (option 3) has the most positive effect on survivability of the frigate. This makes sense, as it is better to counter threats at longer ranges. Range of the radar and the medium range SAM are additional significant factors.

Use of the UAV in AAW operation does not have a significant effect on the frigate's survivability. Our purpose of including a UAV in the scenario is to explore whether a UAV provides early warning for the frigate to counteract an enemy threat. As a result of the analysis, the presence of the UAV does not appear to be a significant factor in AAW mission in terms of frigate's survivability. Longer range UAVs with greater surveillance capabilities may have more effect, but they are not explored in this study.

2. Factor Significance in the Number of Enemy Casualties

Table 12 displays the significant factors in the number of enemy casualties and their rankings. The results are almost the same as the previous ones.

Table 12. Summary of the Factor Significance for Number of Enemy Casualties.

Factor Name	Main Effects Model	Second Order Model
CIWS/PDMS Selection	1	1
Range of Long Range SAM	2	2
Number of Enemy Aircraft	3	3
Number of Land Based ASMs	4	-
SAM Option	5	4
Range of Medium Range SAM	6	7
Radar Range	7	8
UAV	-	16

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V. CONCLUSION

A. SUMMARY

This research investigates the effectiveness of combinations of weapons and sensors onboard a frigate in an AAW environment. It also evaluates the effectiveness of an unmanned aerial vehicle for an AAW mission. By doing so our aim is to determine the needed weapon and sensor capabilities before ship hull design is complete to make operational effectiveness independent from physical design considerations.

An AAW scenario was built to evaluate the candidate weapons, sensor capabilities, and use of a prospective UAV in an AAW operation. We ran 25,700 simulated AAW battles in MANA, and the resulting data were imported to the JMP statistical discovery program for analysis purposes. Due to limitations of MANA, a few characteristics of the AAW environment, such as the flight pattern of the missiles and the altitude of the aircraft, could not be represented. We also made assumptions related to enemy tactics and the operational environment. Therefore, this study could not answer all questions related to the capabilities needed for AAW operations. It does, however, provide useful insights about weapon and sensor employment onboard an AAW frigate.

The result of this analysis shows that the most important design factor for frigate AAW operations is the selection of CIWS or PDMS. Moreover, it shows that PDMS is superior to CIWS. This study also posits that the range of the SAMs, the combination of the SAMs onboard, and radar range have significant impacts on the success of an AAW operation. In addition, this research provides evidence that the use of a medium range UAV in an AAW environment does not significantly contribute to mission success.

B. ANSWERING RESEARCH QUESTIONS

The research questions introduced in the beginning of the thesis are as follows:

1. Among a set of air defense weapon systems alternatives, what is the most effective combination for a future AAW frigate design?
2. How effective are Point Defense Missile Systems (PDMS) compared to Close-in Weapon Systems (CIWS) with different weapon configurations?
3. Does employing a prospective unmanned aerial vehicle (UAV) onboard AAW frigates have significant advantages in an AAW mission?
4. What is the probability of survivability against enemy air assets with different weapon combinations?
5. What are the strengths and drawbacks of utilizing Map Aware Non-Uniform Automata (MANA) to construct realistic scenarios for evaluating AAW effectiveness of naval ships?

To answer the first question, we vary the SAM options and presence of CIWS or PDMS onboard a frigate. As a result, long range and medium range SAMs and the PDMS are the best mix of air defense weapon systems, in addition to the main gun. The range of the long range missile should be more than 154,000 meters.

For the second question, we vary the presence of PDMS and CIWS onboard a frigate. The PDMS' defensive capabilities are superior to CIWS in terms of both survivability and number of enemy casualties. It is also discovered in the analysis that selection of the CIWS has the greatest negative impact on the survival probability.

Interestingly, employment of a UAV for an AAW mission does not contribute to success of the operation. In each analysis, presence of the UAV was either excluded from the significant factors or it has less significance on the response surface.

The previously stated mix of the weapons provides the best survival rate. Selection of the short range SAM rather than medium range SAM reduces the probability of survival, but it still provides a fairly good survival rate. By contrast, employment of CIWS instead of PDMS or selecting the pair of medium and short

SAMs instead of long and medium range SAMs causes an extreme decrease in the survival probability.

Addressing the final question, MANA has many strengths in combat simulation. It has a straightforward user interface to simulate many aspects of combat, such as setting up a weapon and sensor capabilities, as well as defining the communication lines' characteristics. Nonetheless, it has several drawbacks, especially those related to aerial platforms and weapons. For example, simulation of the flight pattern of the missiles and altitude of the aircraft are not included in MANA. The effectiveness settings of a gun with high rate of fire could also be more straightforward in the model setup.

C. FURTHER RESEARCH

Classified information is not included in this study. For future work, classified information such as probability of hit for a particular weapon or the detection probability of radars can be included in the model to get more precise results.

We explore the effectiveness of a prospective UAV in an AAW environment for detection purposes. These UAVs can be loaded with weapons and they can serve in any environment. For future models, armed UAVs can be simulated in a multi-threat (air, surface, and sub-surface threats) environment. And, as previously mentioned, longer range UAVs with greater sensor capabilities can be assessed for their value to an AAW mission.

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